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SOLAR RADIATION AS A METEOROLOGICAL FACTOR¹

By HERBERT H. KIMBALL

SYNOPSIS

Variations in the earth's solar distance cause variations in the intensity of solar radiation at the outer limit of the earth's atmosphere of very nearly 3.5 per cent on each side of the mean, with the maximum early in January and the minimum early in July.

Variations in solar declination cause seasonal variations in the daily totals of solar radiation as measured at the surface of the earth, which are small at the Equator, but increase rapidly with latitude. At Habana, Cuba, latitude 23° 09' N., the average daily amount at the time of the summer solstice is about double that at the time of the winter solstice; at Washington, D. C., latitude 38° 56' N., the corresponding ratio is about 3.5; at Stockholm, Sweden, latitude 59° 21' N., it is about 20, and at Slutzk, Union of Socialist Soviet Republics, about 40.

Following explosive volcanic eruptions the great quantity of dust thrown into the atmosphere, some of it to great heights, has diminished the intensity of the direct rays of the sun as received at the earth's surface from 15 to 25 per cent for periods of several months. Such explosions, with their accompanying dust clouds, occurred in 1883, 1888-1891, 1902, and 1912, and a slight cooling of the earth as a whole seems to have followed. On the other hand, there have been no such eruptions since 1912, or during a period of nearly 20 years, and Ångström is of the opinion that on account of the small amount of dust now present in the stratosphere the temperature of the earth should be slightly higher than usual.

For solar constant values it has been claimed that periodicities of from 68 to 8 months exist, with amplitudes of from 0.005 to 0.014 calories, or about 0.3 to 0.7 per cent of the mean value. Also, that there are short-period trends in values, with an average length of five days and an average amplitude of 0.8 per cent. To these short-period trends of less than 1 per cent in magnitude, have been attributed the "Major changes in weather."

A careful study of these various variations in the intensity of solar radiation leads to the conclusion that weather changes are brought about, not by short-period trends of less than 1 per cent, but by the manyfold difference in the intensity of the solar radiation received by the earth in equatorial and polar regions. As a result great temperature differences exist between these regions. Gravity causes the heavy cold air to displace the lighter warm air at the surface, and a polar-equatorial circulation is set up, turbulent in character, especially in winter when the temperature difference is most marked. Well-defined movements of this character are to be found on the weather maps of the different countries, and examples are shown in this paper in reproductions of weather maps for the United States. It is to studies of this turbulent polar-equator movement of air that meteorologists look for improvements in weather forecasting, and it is for such studies that the meteorological work of the Jubilee International Polar Year 1932-33 is now being organized.

INTRODUCTION

Although in this paper solar radiation is to be considered from the standpoint of the meteorologist, there are certain astrophysical and astronomical facts that also must be kept in mind.

Thus, astrophysical research has shown that the sun is a hot, luminous body, perhaps gaseous throughout, with its outer layers rotating about the solar axis at

different rates in different latitudes. The quality of solar radiation is about that of a black body at a temperature of 6,000° A. This may therefore be taken as the effective temperature of the sun. The temperature of its center, on account of the enormously high pressure that must there prevail, is variously estimated to be from thirty to sixty million degrees.

The sun radiates, we are told, 3.79×10^{33} ergs of energy per second, corresponding to a loss of about 4,000,000 tons of mass per second. Of this vast amount of energy the planets and their satellites intercept about 1/120,000,000, and the earth about 1/2,000,000,000, or 4.1×10^{16} gram-calories per second.

What becomes of all the solar radiant energy except that intercepted by the planets and their satellites, and how the sun maintains this enormous output of energy without apparent impairment of its resources, while interesting problems, will not be considered here. Rather, we shall confine our attention to the one 2-billionth part that is intercepted by the earth, and which is of vital interest not only because it is the source and the support of all life on the earth, but also because it is the source of weather and climate.

ANNUAL VARIATIONS IN SOLAR RADIATION INTENSITY RECEIVED BY THE EARTH

The earth is at its mean solar distance of approximately 93,000,000 miles twice each year—in 1931 on April 4 and October 5. It was nearest to the sun on January 3, and farthest from it on July 6. The ratio of the longest to the shortest distance is 1.034, and since the radiation intensity varies inversely as the square of the distance from the radiating body, other things being equal its intensity early in January should have been nearly 7 per cent higher than in early July. Therefore solar radiation received by the earth has an annual variation in intensity of about 7 per cent, and we in the Northern Hemisphere are now favored by the fact that the maximum intensity occurs during our winter.

Besides the annual variation in the earth's solar distance there is also the annual variation in the sun's apparent declination due to the inclination of the earth's axis of rotation to the plane of the ecliptic, in consequence of which the position of the sun in the heavens coincides with the plane of the terrestrial equator at the time of the equinoxes only. From March 21 to September 21 the sun is north of the terrestrial equator, or its declination is north, and during the remainder of the year it is south. During the summer months, therefore, the sun's rays strike the surface of the earth in the Northern Hemisphere at a smaller angle from the vertical, and thus have a shorter path through the atmosphere during most of the day than during the winter months; also,

¹ Presented before Section B, A. A. A. S., at a joint session with the American Meteorological Society at New Orleans, La., on December 30, 1931.

the sun is above the horizon a greater number of hours. The reverse, of course, is the case in the Southern Hemisphere, which has its winter while the Northern Hemisphere has its summer.

Thus, from variations in the solar declination there results a second annual variation in the vertical component of solar radiation intensity, which variation itself varies in amount with latitude. In consequence, for the average daily totals of solar radiation as received on a horizontal surface the annual variation is slight at the Equator, at Habana, Cuba, the midsummer totals are about double those for midwinter, at Washington, D. C., they are 3.5 times as great, and at Stockholm, Sweden, and Sloutzk, Union of Socialist Soviet Republics, the ratios are 20 and 40, respectively.

ATMOSPHERIC DEPLETION OF SOLAR RADIATION

Besides the annual variation in solar radiation intensity due to the earth's position in its orbit, and that due to solar declination, there are irregular variations owing to changes in the constituents of the atmosphere. In general, these constituents may be divided into three classes, as follows:

(1) Atmospheric gases; (2) solid particles, principally dust; and (3) condensed gases, principally water.

The constituents of the atmosphere deplete the solar radiation that passes through it in three ways, as follows:

(a) Scattering by atmospheric gas molecules, the law of which has been developed in a workable form by Raleigh and King.

(b) Absorption by atmospheric gases, the laws for which have been determined by Fowle and others, so that the depletion may be computed provided we know the atmospheric content of each of the absorbing gases, of which the principal are water vapor, ozone, and carbon dioxide.

(c) Scattering by solid particles and condensed gases. Ångström has developed the law for scattering by dust

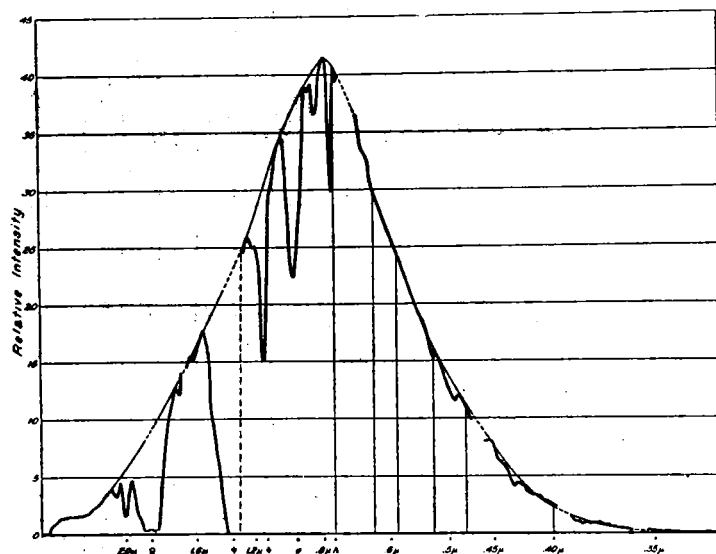


FIGURE 1.—Bologram of solar radiation

particles, provided their diameters are known, and has put it in a convenient form for computing. Unfortunately, atmospheric dust particles vary in size. Those due to explosive volcanic eruptions, and also dust particles from city smoke, average much larger in diameter than ordinary atmospheric dust, for which Ångström's law has been developed.

The extent of the depletion of radiation both by scattering and by absorption varies with the wave length. Therefore, for its determination spectro-bolometric measurements are necessary.

Figure 1 is a spectro-bologram of solar radiation obtained by the Astrophysical Observatory of the Smith-

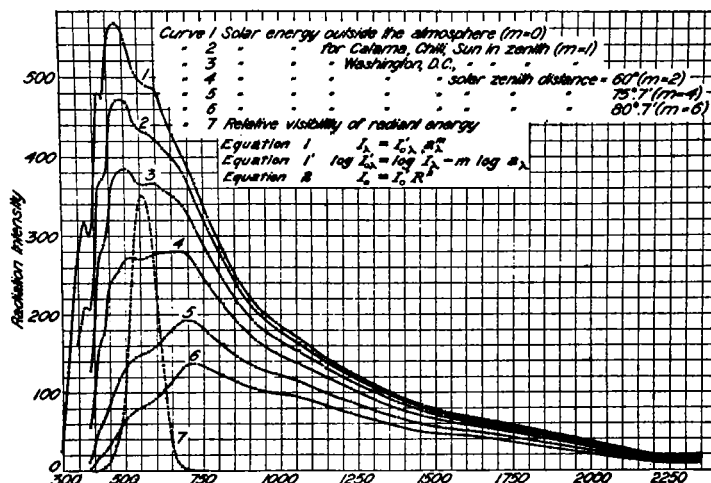


FIGURE 2.—Normal solar radiation energy curves

sonian Institution by means of a 60° ultra-violet crown-glass prism (1). Note the depressions in the curve caused by absorption of energy in the water-vapor bands. In one of these the position of the zero line of the curve has been redetermined. Note also that the wave-length scale is more open at the short-wave or ultra-violet end of the bologram than at the infra-red end. In Figure 2 the wave-length scale has been made uniform throughout and is reversed in direction from that in Figure 1, so that wave lengths here increase from left to right. In addition to the fact that the water vapor absorption bands are not here shown, the energy distribution with respect to wave length has been materially changed, so that for curve 1, "Solar energy outside the atmosphere" (2), the maximum intensity is in the blue. In curve 2 (3), for radiation intensities measured at Calama, Chile, and for curves 3 to 6, inclusive, for intensities measured at Washington, D. C. (4), with the sun at increasing angular distances from the zenith, the maximum of the energy curves is shifted successively from the blue through the green, yellow, and orange to the red, which indicates why, as the sun approaches the horizon, it often assumes a reddish hue.

However, the apparent color of the sun can not be determined from the wave length of the maximum of the spectrum energy curve alone. Curve 7, Figure 2, gives the relative visibility of radiant energy of different wave lengths. It has a decided maximum in the green, and from this it has been argued that if we could view the sun from outside the earth's atmosphere its color instead of being blue, as Langley claimed, would be green.

THE DETERMINATION OF THE VALUE OF THE SOLAR CONSTANT OF RADIATION

Spectro-bolometric measurements of the intensity of solar radiation throughout the solar spectrum, made at the surface of the earth, form the basis for determinations of the intensity before it entered the earth's atmosphere. The theory of the determination is simple, but the observational work is tedious.

Referring to Figure 2, curves 4, 5, and 6 represent solar spectrum energy curves based on spectro-bolograms ob-

tained with the sun at zenith distances 60.0° , 75.7° , and 80.7° . The corresponding length of the paths, m , traversed by the solar rays to reach the surface of the earth, expressed in terms of the length when the sun is in the zenith, are, respectively, 2.0, 4.0, and 6.0. The depletion of solar radiation of different wave lengths is expressed by the equation

$$(1) \quad I_\lambda = I'_{0\lambda} a_\lambda^m$$

where $I'_{0\lambda}$ is the intensity of radiation of wave length λ before it entered the atmosphere, a_λ the atmospheric transmission coefficient for the given wave length, and

Pyrheliometric readings made at the time the bolograms are obtained make it possible to express the radiation intensity they represent in absolute heat units, and the ratio of their areas, after making allowance for band absorptions, to the area of the bologram for zero atmosphere, make possible the determination of the intensity outside the atmosphere, I'_0 , with considerable accuracy. Then for the solar constant

$$(2) \quad I_0 = I'_0 R^2,$$

where R is the earth's radius vector at the time the measurements were made, in terms of its mean value.



FIGURE 3.—Solar constant values

I_λ the measured intensity for the same wave length at the surface of the earth.

Equation (1) may also be written

$$(1') \quad \log I'_{0\lambda} = \log I_\lambda - m \log a_\lambda$$

which is the equation of a straight line. Therefore, if the atmospheric transmission remains constant throughout a half-day period, from several bolometric records it will be possible to extrapolate values of I_λ to zero atmosphere, and thus to construct the spectrobologram for solar radiation outside the atmosphere.

During the years 1902 to 1907, inclusive, 44 determinations of the value of the solar constant were made at the Astrophysical Observatory of the Smithsonian Institution, in Washington (5). Seven of these were graded poor. Of the remaining 37 values the mean, expressed in gram calories per minute per square centimeter, is 1.968, the maximum 2.252, the minimum 1.814, giving a range of 0.438, or 22 per cent of the mean value. There seemed to be such strong evidence of marked changes in the value of the solar constant that the Smithsonian Institution established an observing station on Mount Wilson, Calif., where solar constant determinations were

made during the summer and fall months from 1905 to 1920, the year 1907 excepted, and at Bassour, Algeria, in 1911 and 1912. A few determinations were also made on Mount Whitney in 1909 and 1910, and at Hump Mountain in North Carolina in 1917-18. The mean of all values obtained to the end of 1920, those at Hump Mountain excepted, is 1.936 gram calories per minute per square centimeter, and the range is from 2.133 to 1.780, or 18 per cent (6).

Still impressed by the marked variations in the value of the solar constant, in July, 1918, the Smithsonian Institution established an observing station at Calama, Chile, where it was hoped that solar constant values could be determined throughout the year instead of during the summer and fall months only, as was the case at Mount Wilson. During the first year the fundamental method followed at Mount Wilson was employed. Considerable variations in the solar constant were found, the maximum value being 2.018, the minimum 1.865, giving a variation of about 8 per cent of the mean (7).

It was recognized by the Smithsonian Institution that it is a weakness of the spectrobolometric method of determining the value of the solar constant that it is necessary to assume that the atmospheric transmission does not change during the few hours in the morning or the afternoon required to obtain holograms over a sufficient range of air mass values to permit of accurate extrapolation to zero atmosphere. This led to the development of a new method of determination (8), which is independent of changing atmospheric transmissibility, and which therefore enables determinations to be made on days when a clear sky early in the half-day period becomes bad later, or vice versa, as well as on continuously clear days.

Briefly, from a measurement of the brightness of the sky in a 15° zone about the sun, and a spectrobolometric determination of the absorption of solar radiation by water vapor and other gases of the atmosphere, a so-called function, F , is obtained, by means of which, in connection with empirically determined curves, the atmospheric transmission may be found for about 40 different wave lengths and the solar spectrum energy curve extrapolated to zero air mass.

A disadvantage of this method is that the curves correlating the function F with the transmissions a_λ require a long series of spectrobolometric observations for their determination. It has been used at Calama and Mount Montezuma, Chile, since the end of June, 1919. The earlier determinations have undergone several series of corrections, however, so that up to and including July, 1927, only monthly mean values are now available (9). The monthly means, and daily values since August 1, 1927, are plotted in Figure 3. These latter are kindly furnished the Weather Bureau each day for publication on the Washington edition of the Daily Weather Map.

The maximum of 1,007 daily determinations made on Mount Montezuma, Chile, during the latter period is 1.966 gr. cal. per minute per square centimeter, and the minimum is 1.903, giving a range of 0.063, or 3.2 per cent of the mean value, 1.940. Both the extreme values were rated $S-$ by the observer, signifying that the sky conditions at the time were not the best. These 1,007 determinations give a standard deviation of ± 0.00856 . There is evidence of periodic variations, however, and if we confine our attention to 157 determinations made between November 12, 1929, and June 26, 1930, in which there is little evidence of such variation, the standard deviation is ± 0.00536 and the probable error a little less than ± 0.2 per cent. This is an exceedingly small error.

Recalling that the absolute value of the determination rests on the rate of change in temperature of the Smithsonian silver disk pyrheliometer when exposed to solar radiation, that the rate is only about 4°C. in 100 seconds, and is measured by a mercurial thermometer graduated on the stem to tenths of a degree, it is evident that these readings must be accurate to the tenth of a scale division, or to 0.01°C. This accuracy is obtained by reading two pyrheliometers on alternate minutes, which reduces the probable error by $1/\sqrt{2}$. However, small errors in the determinations of atmospheric transmissibility for the different wave lengths are bound to occur.

In a publication entitled "Weather dominated by solar changes" (Smithsonian Miscellaneous Collection, vol. 85, No. 1, Washington, 1931), Doctor Abbot sum-

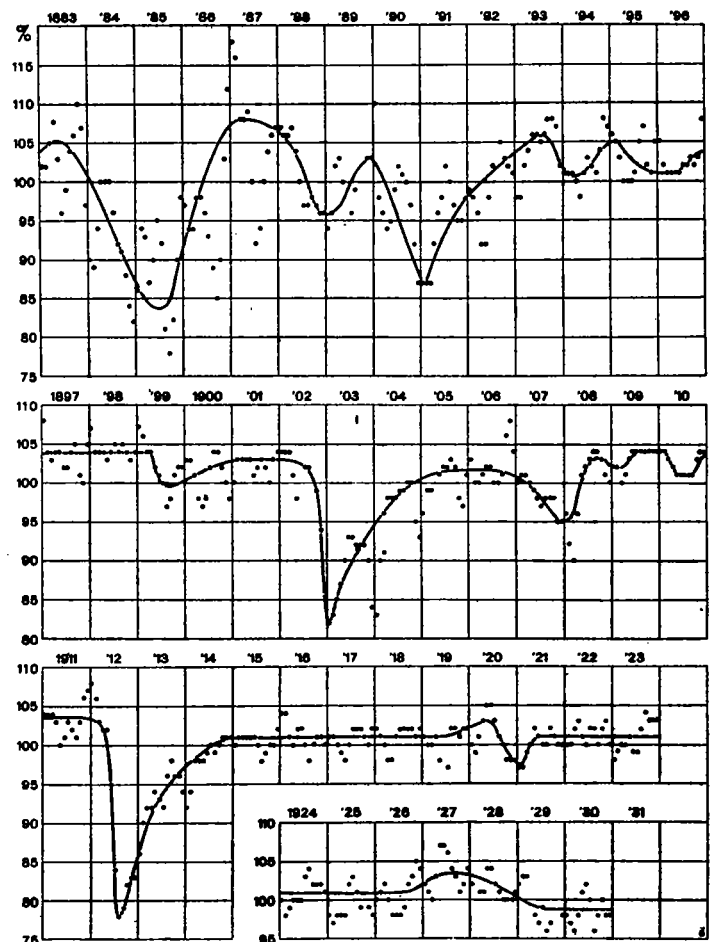


FIGURE 4.—Monthly averages of solar radiation intensity measured at the surface of the earth, expressed as percentages of the monthly normals

marizes the results of his studies of periodicities in solar constant values, basing his conclusions principally on the values obtained in the years 1924 to 1930, inclusive. He finds periodicities of 68, 45, 25, 11, and 8 months, respectively, in length, with amplitudes of from 0.3 to 0.7 per cent of the mean value, and projects them into the future to predict the trend of solar constant values to the end of 1932. The values actually obtained in 1931 are considerably lower, and have less range than was predicted.

In this publication Abbot states "I shall present evidence to show that weather * * * is caused chiefly by the frequent intervals of actual change in the emission of radiation within the sun itself." Then after discussing sequences of rising and falling solar radiation intensity, which he finds to occur in short intervals,

averaging five days, and in amount exceeding 0.4 per cent, and averaging 0.8 per cent of the value of the solar constant, he makes the further statement that "Major changes in weather are due to short-period changes in the sun." The reasoning by which this conclusion was reached is somewhat involved, and those interested are referred to the original paper for its elucidation.

Studies by forecasters and others at the United States Weather Bureau do not confirm the contention that "Major changes in weather are due to short-period changes in the sun."

VARIATIONS IN THE MEASURED INTENSITY OF SOLAR RADIATION RECEIVED AT THE SURFACE OF THE EARTH

In Figure 4 are shown monthly averages of solar radiation intensity based on measurements made at several different points in the Northern Hemisphere, and expressed as percentages of the normal intensities at the respective stations. In the earlier years systematic measurements are available from only one station, namely, Montpellier, France. In later years, measurements from as many as eight stations were available (10), but for the years since 1923 they are available to me from only four stations—Washington, D. C., Madison, Wis., and Lincoln, Nebr., in the United States, and Warsaw in

clear, and, in consequence, should deplete the incoming solar radiation less than usual. As a result the earth as a whole should experience a slight rise in temperature. This seems to be true of North America, while Europe has been cold and wet. Such apparent anomalies are not unusual, however, and are attributable to modifications in the atmospheric circulation.

It should be stated that of the radiation scattered from the direct rays of the sun by dust, perhaps one-half eventually finds its way to the earth's surface as diffuse radiation.

THE HEAT BALANCE OF THE ATMOSPHERE

In Volume III of his Manual of Meteorology, page 106, Figure 50, Sir Napier Shaw reproduces "W. H. Dine's (13) scheme of transfer of energy between the sun, the earth, and space," which is here shown in Figure 5.

- (1) Short-wave, or solar radiation:

A = solar radiation received at the outer limit of the

$$\text{atmosphere,} = 1.94 \times 1440 \times \frac{\pi R^2}{4\pi R^2} = 700 \text{ gram calo-}$$

Per cent

ries per square centimeter per day..... = 100

D = amount returned to space by scattering and re-

flexion..... = 50

C = amount absorbed by the gases of the atmosphere..... = 8.5

B = amount expended at the surface of the earth..... = 41.5

$D + C + B$ = total short-wave radiation accounted for..... = 100.0

- (2) Long-wave, or low-temperature radiation:

E = amount radiated to the earth by the atmosphere..... = 47.5

M = amount scattered and reflected to the earth by the atmosphere..... = 8.5

$[B] + E + M$ = total radiation reaching the earth's surface..... = 97.5

G = amount radiated from the earth's surface..... = 69.0

L = amount transferred from earth to atmosphere through conduction and evaporation..... = 28.5

$G + L$ = total transmitted from earth to atmosphere..... = 97.5

F = amount radiated from the atmosphere to space..... = 39.0

K = amount transmitted through the atmosphere to space..... = 11.0

$[D] + F + K$ = total from atmosphere to space..... = 100.0

It is significant that of the total radiation reaching the surface of the earth ($B + E + M$), B , short-wave radiation..... = 41.5

And $E + M$, long-wave radiation..... = 56.0

Also, of the total radiation expended in the atmosphere, ($C + L + H$), C = short-wave radiation..... = 8.5

And $L + H$, long-wave radiation..... = 78.0

When we consider the secondary part played by the short-wave radiation in heating the atmosphere, and the many factors that enter into the determination of the relative values of D , C , and B , such as cloudiness, character of the ground cover (for example, dark or light colored soil, vegetation, sand, or snow), the water-vapor content and dust content of the atmosphere, etc., we may well question how a variation of less than 1 per cent in the value of A in a period of four to five days can have sufficient effect upon the value of either $M + E + B$ or upon $L + H + C$ to become apparent in the air temperature at a given place.

DAILY TOTALS OF SOLAR RADIATION RECEIVED AT THE SURFACE OF THE EARTH

In Figure 6, curve 1 shows for the entire year the daily totals of solar radiation received at the outer limit of the atmosphere for the latitude of Washington, $38^\circ 56' N$. Broken lines show what would have been the daily totals in midsummer and in midwinter, had the earth been at its mean solar distance. Curve 2 gives the daily totals with clear skies measured at Twin Falls, Idaho, latitude

THE HEAT-BALANCE OF THE ATMOSPHERE

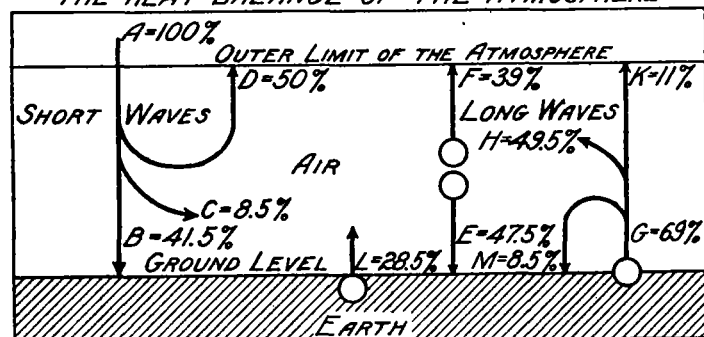


FIGURE 5.—The heat balance of the atmosphere

Poland. The measurements show marked periods of depression in the solar radiation intensity, as follows:

(1) In 1884–1886, following the eruption of Kratatoa Volcano in 1883. In 1885 the solar radiation was about 20 per cent lower than in 1883 and 1887.

(2) In 1888–1891, during a period of exceptional volcanic activity, but without any such outstanding eruption as that of Kratatoa. The decrease in intensity at the end of 1890 was about 15 per cent.

(3) In 1902–3, following the eruption of Pelée, Santa Maria, and Colima in 1902, with a sharp depression in solar radiation intensity at the end of 1902 of 20 per cent.

(4) In 1912–13, following the eruption of Katmai Volcano in June, 1912, which caused a decrease in solar radiation intensity in the following month of nearly 25 per cent.

The researches of Abbot (11), Humphreys (12) and others, indicate that these and earlier volcanic eruptions have been followed by a slight fall in the temperature of the earth as a whole, and especially at continental stations.

On the other hand, Ångström in a recent "Notiser" calls attention to the fact that since 1912, or for nearly 20 years, there have been no marked volcanic eruptions of an explosive character, such as throw great quantities of dust into the atmosphere. Therefore, the upper atmospheric layers, or the stratosphere, must now be unusually

42° 29' N., altitude about 4,300 feet, and curve 3 gives corresponding values for Washington, D. C., altitude about 400 feet.

Curve 4 gives the normal daily values with average skies at Twin Falls, curve 5 the corresponding values for Washington, and curve 6 summarizes measurements made by the weather bureau at the University of Chicago, latitude 41° 47' N., altitude 688 feet.

On the normal values of curve 5 are superposed the weekly averages for Washington for the year 1925. These values show for the weeks centering on March 22 and 29 a variation at Washington from 111 to 56 per cent of the normal values, or 30 per cent of the amount

horsepower-hours, and at Washington to nearly 30,000,000. Also, on an average day in midsummer at Twin Falls the daily total is equal to about 27,000,000, and at Washington to 20,000,000 horsepower-hours. If it were possible to concentrate this energy as water power is concentrated, industry would have at its command an inexhaustible source of power.

RELATION BETWEEN INSOLATION AND AIR TEMPERATURE

The annual curves of daily totals of solar radiation and air temperature may be expressed by equations of the Fourier type (14). Thus, the equation for Q_m , Figure 6,

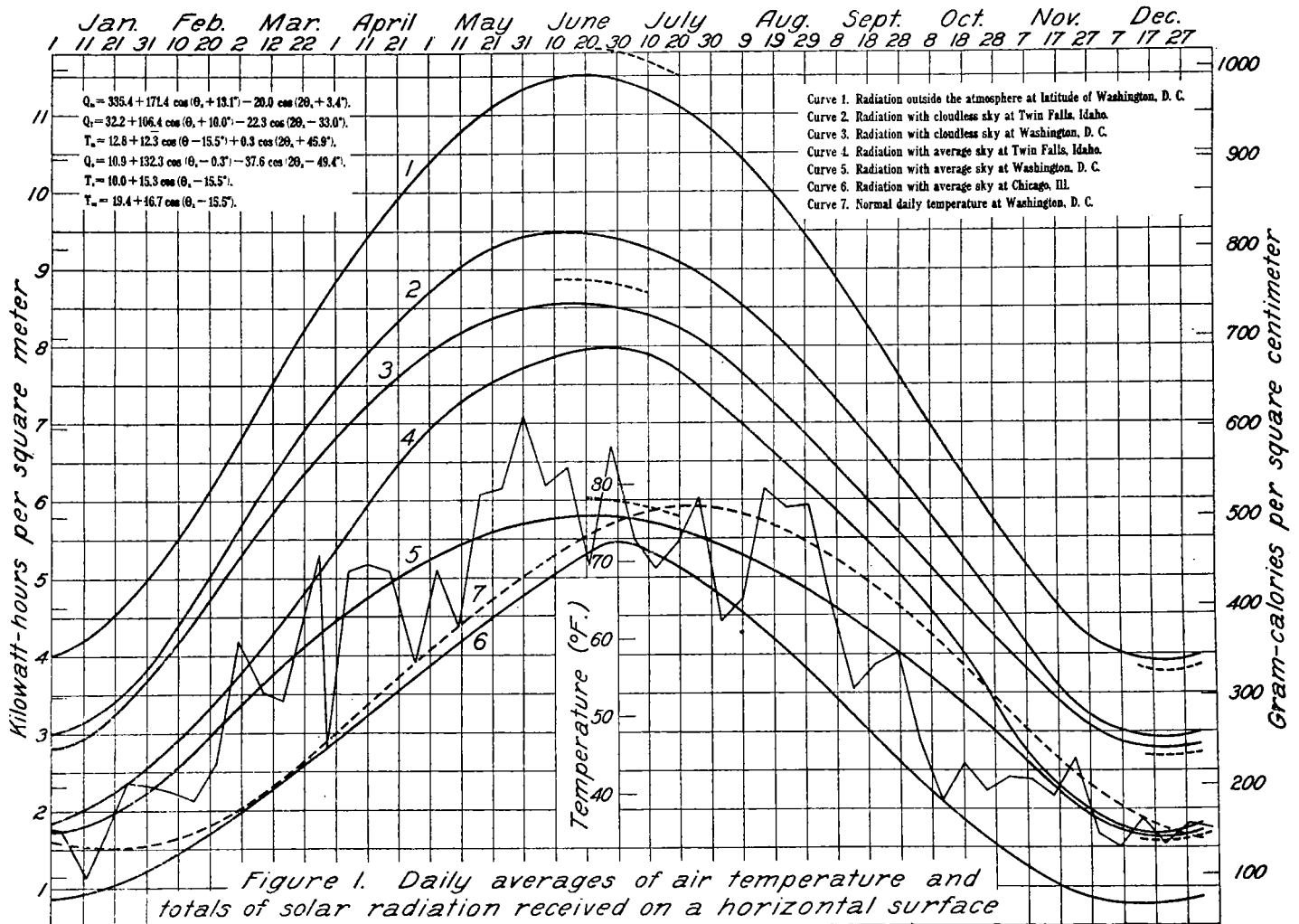


FIGURE 6.—Annual curves of daily totals of solar radiation

received at the outer limit of the atmosphere. Daily values show on September 3 to 4, 1931, at Washington, a variation from 35 to 115 per cent of the normal value, or 41 per cent of the receipt at the outer limit of the atmosphere.

These daily and weekly variations in the total solar radiation received at the surface of the earth are due principally to the amount of clouds present in the atmosphere. Since extensive cloud areas usually accompany storms, considerable portions of a continent may at a given time be covered by clouds.

SOLAR ENERGY RECEIVED PER SQUARE MILE

It is interesting to note that on a cloudless day in midsummer at Twin Falls the daily receipt of solar energy per square mile of surface is equal to nearly 33,000,000

represents curve 5, and that for T_m represents curve 7 (15). Also, we may compute the equation for Q_s , the radiation available for heating the atmosphere after deducting from Q_m the loss due to reflection, the amount expended in evaporation, and the amount radiated to space. We may also compute Q_s , the radiation that should be available for heating the atmosphere if the ground were continuously covered with snow from December 1 to February 28, inclusive, and the resulting temperature curve represented by T_s . Likewise, from the equation for curve 3 we may compute the radiation and temperature curves Q_{oc} and T_{oc} for continuous sunshine at Washington.

The equation for T_s shows that with a continuous snow cover on the ground at Washington during the three winter months the midwinter temperatures would be 5° C.

colder than with an average snow cover, due to the greater loss of radiation through reflection, which accords with observations. With no snow on the ground zero temperature Fahrenheit has never been recorded at Washington, while with a snow cover a temperature of -15° F. has been recorded.

Similarly, with continuous sunshine the equation for T_{oc} gives midsummer temperatures 11° C. or 20° F.,

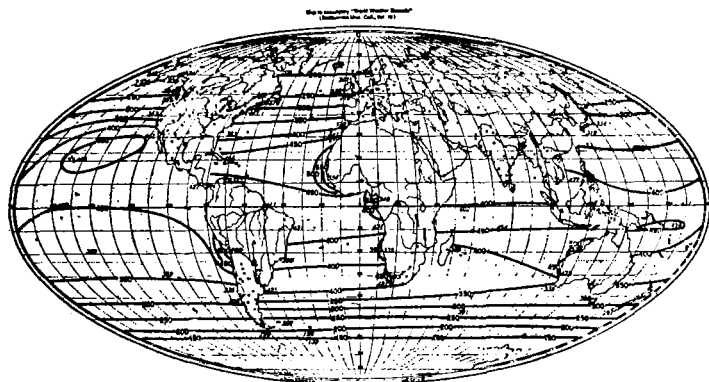


FIGURE 7.—Isopleths of the total solar radiation (direct + diffuse) received on March 21, with average cloudiness (Gr. cal. per day per sq. cm.)

warmer than at present, giving daily means of 96° F., or temperatures representing desert conditions.

In the above equations, $\theta_z = 0$ on July 5.

SOLAR RADIATION AS THE SOURCE OF WEATHER AND CLIMATE ON THE EARTH

Such observations as are available do not indicate that variations in the value of the so-called solar constant of radiation, or in the depletion of radiation by changes in the atmospheric transparency have produced marked effects upon the temperature of a given place, or of the world as a whole. However, C. E. P. Brooks, in *Climate Through the Ages*, after reviewing the effect of volcanic dust upon the pressure distribution as well as upon atmospheric temperature, and especially the weakening of the southwest wind over the Atlantic Ocean and western Europe due to the marked decrease in the pressure gradient between the Azores and Iceland following volcanic eruptions, concludes that volcanic dust may explain climatic periods colder than the present.

Attention is invited to the fact that in the equation for Q_r , the annual term is plus, indicating a surplus of radiation over what is required to maintain the annual temperature T_m . Ångström found for Stockholm, that the annual term in the equation for Q_r is minus. It would seem, therefore, that a transfer of the excess of heat in low latitudes is necessary to make up the deficit in high latitudes.

It is difficult to chart daily average values of insolation over the continents for the reason that altitude above sea level is an important factor in determining these values. Only a few radiation measurements have been made at sea, but if we know the average cloudiness, the average water-vapor content and dust content of the atmosphere over the ocean, we may compute the corresponding average solar radiation intensity for a given day at given latitudes with reasonable accuracy. This I have done, using such records of cloudiness, air temperature, and relative humidity for marine stations as are available (16). The results for average cloudy conditions are shown in Figure 7 at the time of the vernal equinox, in Figure 8, at the time of the summer solstice,

and in Figure 9 at the time of the winter solstice. They check satisfactorily with such measurements as have been made.

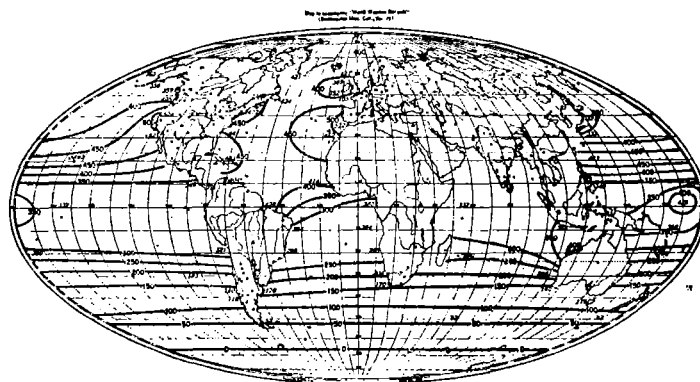


FIGURE 8.—Isopleths of the total solar radiation (direct + diffuse) received on June 21, with average cloudiness (Gr. cal. per day per sq. cm.)

Note the decrease with latitude in the daily totals of solar radiation, which is particularly marked at the time of the winter solstice. As is well known, there results a corresponding decrease in temperature in winter from 70° F. at the equator to -37° F. in the vicinity of the North Pole, and to -51° F. in Siberia, or temperature differences of 107° to 121° F.

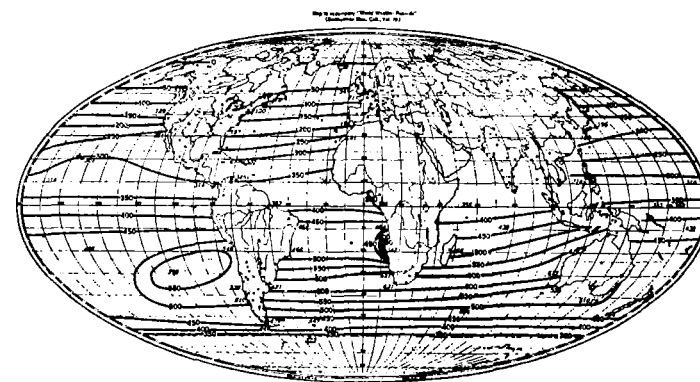


FIGURE 9.—Isopleths of the total solar radiation (direct + diffuse) received on December 21, with average cloudiness (Gr. cal. per day per sq. cm.)

In July the temperature differences are much less. At the equator, over the oceans, the mean temperature is still about 70° F., but over the interior of continents it is 90° F., while at the North Pole it is about 35° F., giving temperature differences over the ocean of only 35° , and from continents to the North Pole of 55° F.

THE POLAR-EQUATORIAL EXCHANGE OF AIR MASSES

When two bodies of air of unequal temperatures lie near each other, gravity causes the cold air to displace the warm air at the earth's surface. In this way atmospheric circulation is initiated, which on a nonrotating globe of uniform surface, might be quite regular. On a rotating globe with an irregular surface like the earth, consisting partly of land and partly of water, and the land surfaces not planes, but mountain peaks and mountain chains separated by deep valleys, the circulation of the air is bound to be turbulent. It is this turbulent interchange of air between the warm and the cold regions on the earth's surface that generates storms and the various phases of weather that accompany them.

Figures 10, 11, 12, and 13 give an illustration of these air movements over the United States and the accompanying weather changes. On the morning of January

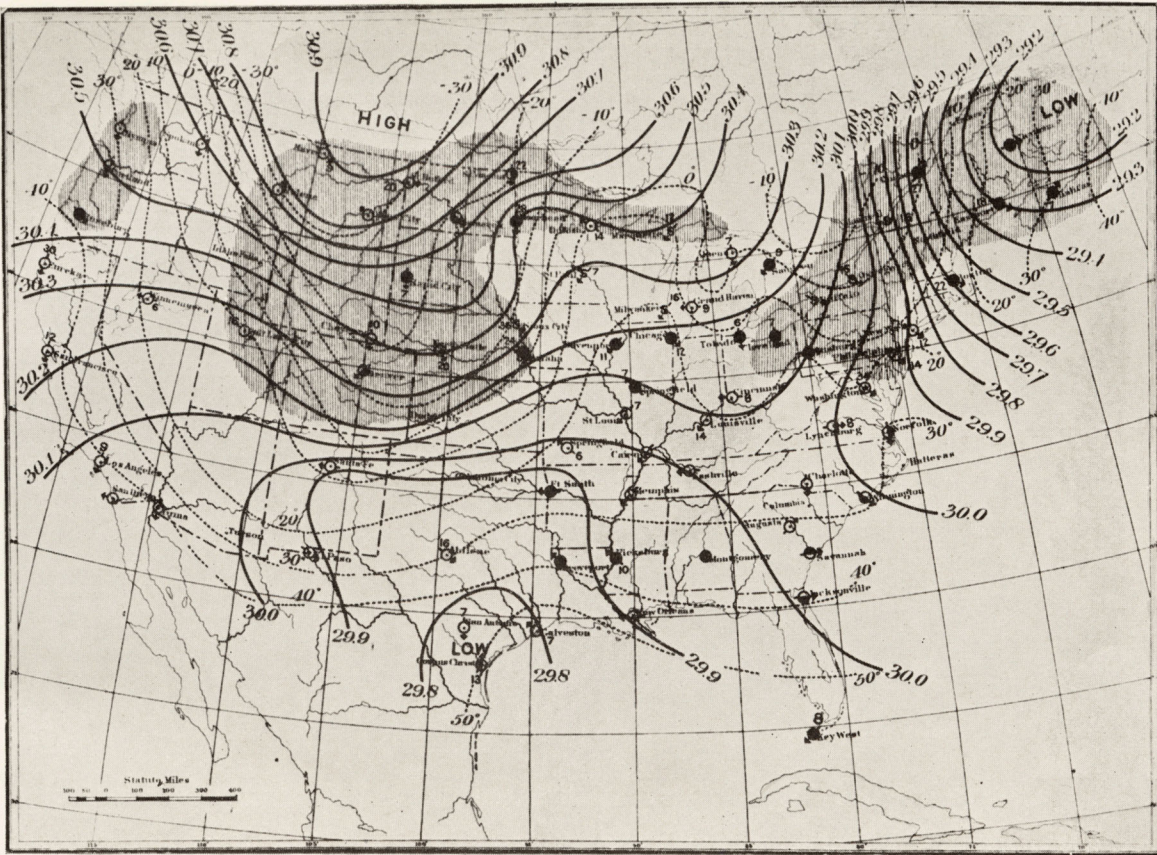


FIGURE 10.—Weather map of the United States for 7 a. m., January 7, 1886

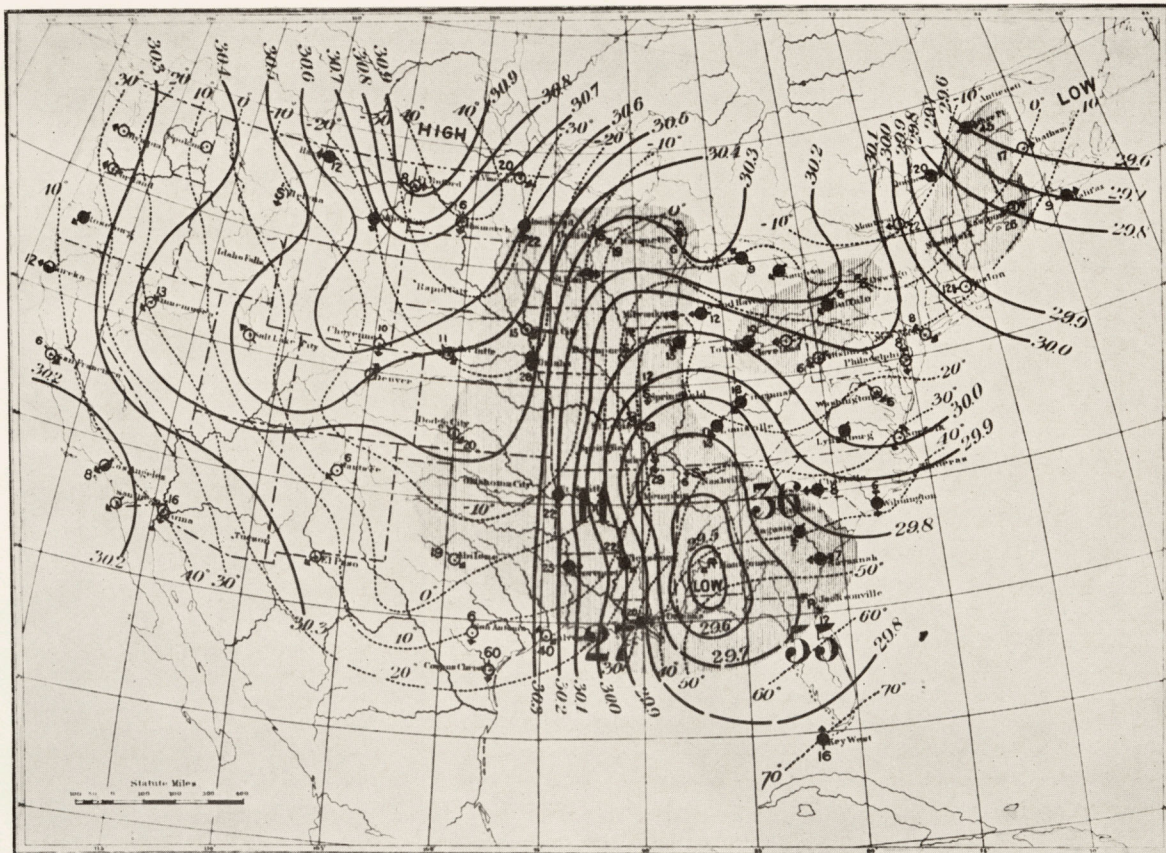


FIGURE 11.—Weather map of the United States for 7 a. m., January 8, 1886

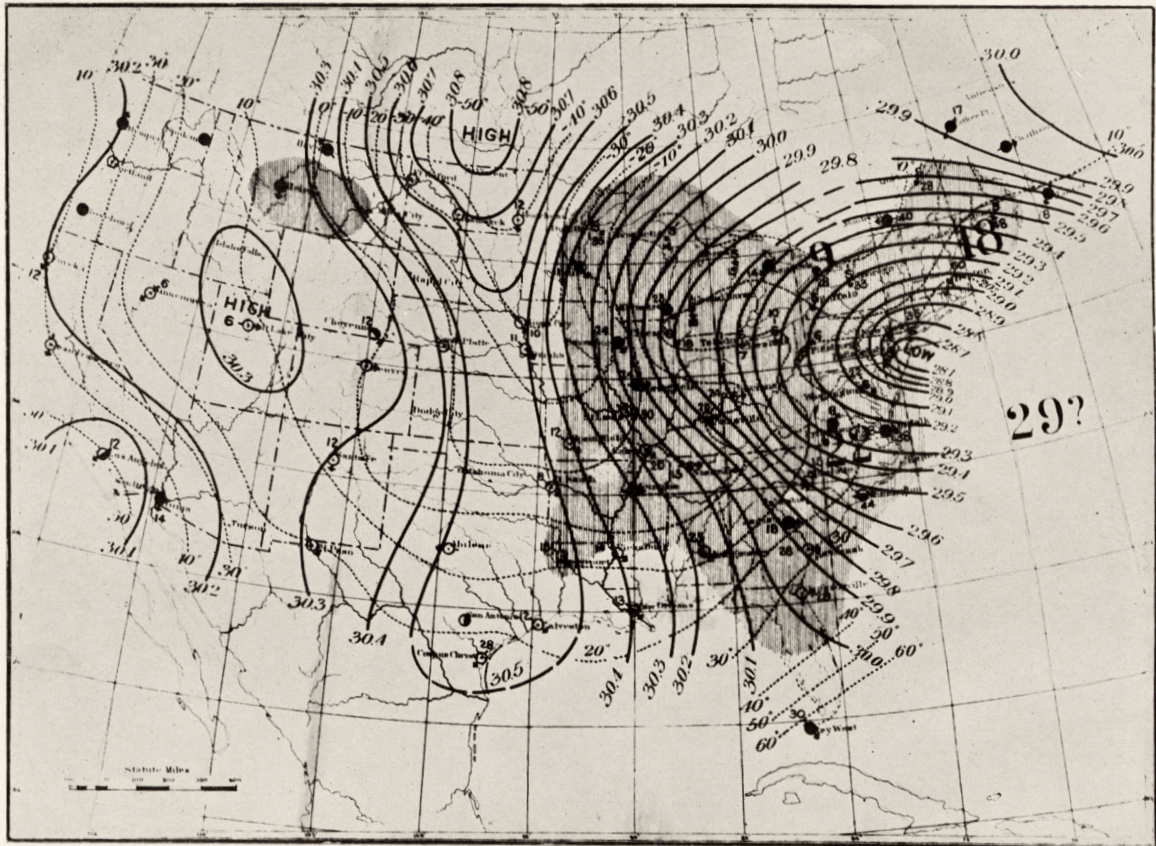


FIGURE 12.—Weather map of the United States for 7 a. m., January 9, 1886

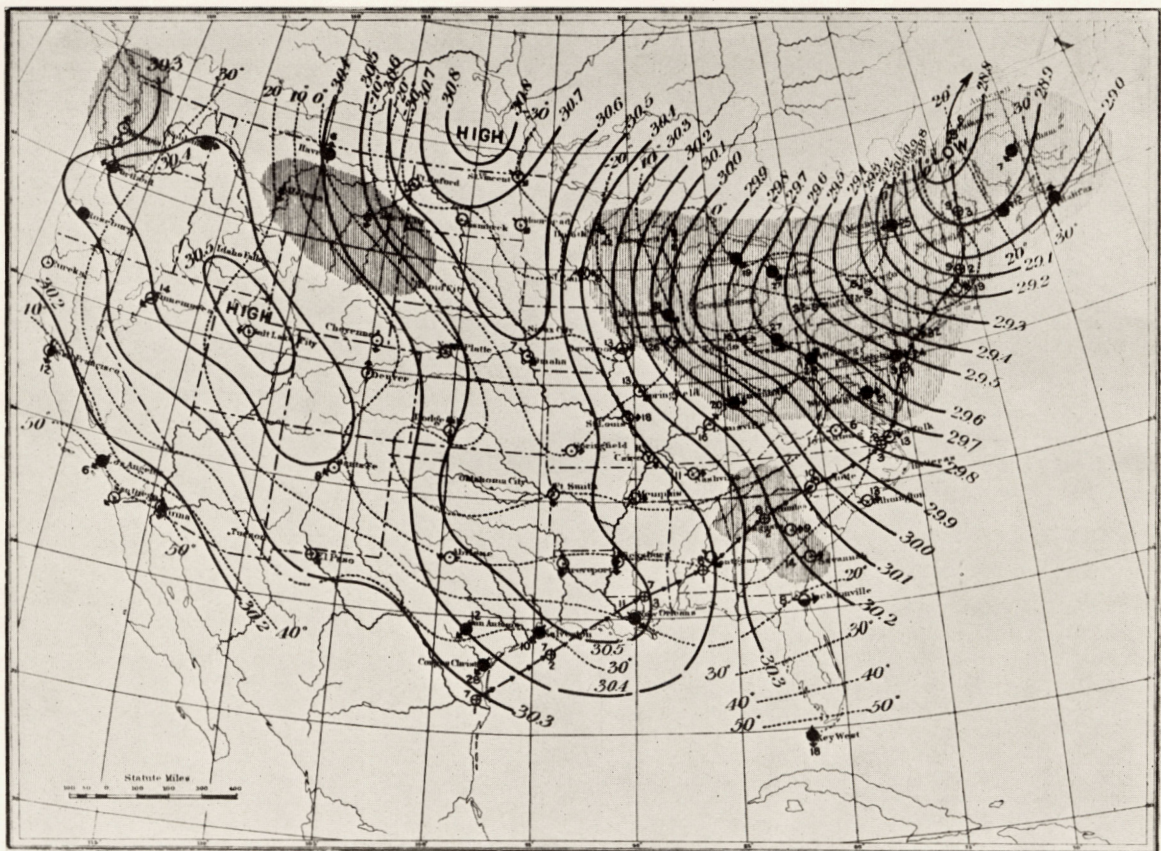


FIGURE 13.—Weather map of the United States for 7 a. m., January 10, 1886

7, 1886, a low-pressure area was passing off the North American coast near the mouth of the St. Lawrence River. Warm south to southwest winds prevailed on its front, and cold winds, generally from the northwest, on its rear. A high-pressure area was overspreading the Rocky Mountain Plateau with winds generally from the north and with temperatures as low as 30° below zero. There were indications that a cyclone was developing on the Texas coast, with winds in the lower Mississippi valley from the southeast.

In the July, 1931, number of the MONTHLY WEATHER REVIEW, Bjorkdal (17) defines *frontal zones* and *fronts*, as follows:

When two air masses each uniformly homogeneous approach each other nearer than about 1,000 kilometers (620 miles), the area between them no longer fulfills the conditions of a homogeneous air mass. A *frontal zone* occurs which can gradually sharpen to a *front*. Fronts are narrow inclined transition zones of the same vertical extent as the air masses. It is essential that the difference of the values on both sides of the front of at least one of the independent elements (temperature, pressure, wind, humidity) is so great that it has an appreciable effect on the great-scale dynamics (of the air mass).

Evidently on the morning of January 7, a *frontal zone* extended from the Texas coast northeastward to Illinois, as shown by the wind directions and temperature lines. On the morning of the 8th, it had sharpened into a *front* which extended northward from near the mouth of the Mississippi to Lake Michigan having a 20° rise in temperature in 24 hours with the south winds to the east and a 30° fall in temperature with the north winds to the west. Large figures show the average temperature in each quadrant of the cyclone.

Note on the 9th the marked development of the low center on this polar front, and its movement toward the northeast. The flow of cold air from the north now covers practically the whole country east of the Rockies, except the extreme northeastern section. The map for January 10 shows temperatures as low in Florida as in New Brunswick, Canada, near the mouth of the St. Lawrence River.

Cyclonic storms of this type often persist for days, crossing oceans from continent to continent, and in rare cases completing the circuit of the globe.

The above are only instances of great major changes which are continually going on in weather conditions all over the earth; although during the spring months, as the temperature difference between the equator and the pole diminishes, the extent and the intensity of the air movements also diminish, and become comparatively weak in summer, just when the effect of solar variability should be at its maximum. Therefore, is it rational to believe that these major weather changes are caused and explained by alleged short-period changes of less than 1 per cent in the intensity of solar radiation? A part if not all of this 1 per cent variation must be set off as caused by inevitable accidental errors, but even if the whole of it were real solar change, can we believe that if this small variation were to cease our major weather changes would disappear also?

The importance attributed by meteorologists to the polar-equatorial exchange of air is attested by the program adopted by the International Meteorological Committee for the Jubilee Polar Year, 1932-33. It is proposed to surround the North Pole with stations so completely equipped and manned that it will be possible to publish hourly values of the principal meteorological

elements. It is also proposed to reproduce all automatic records obtained. Those from polar stations should show the origin of polar fronts, and those from stations in lower latitudes, their progress. Meteorological observations will not be confined to low-level stations, but upper air conditions will be recorded, at mountain stations, and by means of balloons, kites, and airplanes at numerous aerological stations. Also, especial attention is to be given to observations of the aurora, by eye observations, by synchronous photographs at neighboring stations to determine auroral heights, and by spectroscopic observations, with a view to learning more about atmospheric conditions at great heights.

As stated by the chairman of the commission for the polar year (18).

The further that extensions have been made of the dynamical theories of air interaction in moderate latitudes for practical forecasting purposes, the clearer has it become that atmospheric processes in the polar regions of both hemispheres play a predominant part. These regions are very often the source of the surges in the atmosphere whose necessary outcome are the weather variations at low latitudes. An intimate study, therefore, of the behavior of the atmosphere in high latitudes has now become a necessity for the extension in knowledge of weather processes.

It is from studies of this character that meteorologists are attempting to increase their knowledge of the generation and movements of storms and of the weather changes that accompany them.

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